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**The Thesis Committee for Sten Oliver Stray-Gundersen  
Certifies that this is the approved version of the following Thesis:**

**Walking with Leg Blood Flow Restriction: Wide-Rigid Cuffs vs.  
Narrow-Elastic Bands**

**APPROVED BY  
SUPERVISING COMMITTEE:**

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Hirofumi Tanaka, Supervisor

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Sophie Lalande

**Walking with Leg Blood Flow Restriction: Wide-Rigid Cuffs vs.  
Narrow-Elastic Bands**

**by**

**Sten Oliver Stray-Gundersen**

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## **Abstract**

### **Walking with Leg Blood Flow Restriction: Wide-Rigid Cuffs vs. Narrow-Elastic Bands**

Sten Oliver Stray-Gundersen, M.S. Kin.

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Supervisor: Hirofumi Tanaka

Blood flow restriction (BFR) training is becoming a popular form of exercise. The concept is that light-load exercise performed with BFR elicits similar adaptations achieved with traditional heavy-load exercise. Walking exercise in combination with pressurized wide-rigid (WR) cuffs elicits higher cardiac workload and a vascular dysfunction due presumably to reperfusion injury to the endothelium. In contrast, narrow-elastic (NE) BFR bands may elicit different hemodynamic effects, as the limb is able to increase in diameter with increased blood flow accompanying exercise. **Purpose:** To compare the acute cardiovascular responses to two distinct forms of BFR training during light-intensity exercise. **Methods:** 15 young healthy participants (M=9, F=6) performed 5 bouts of 2-minute walking intervals at 0.9 m/s with a 1-minute rest and deflation period between bouts with either WR, NE, or no bands placed on both upper thighs. Cuff pressure was inflated to 160 mmHg in WR cuffs and 300 mmHg in NE bands while no cuffs were used for the control. Beat-by-beat blood pressure and heart rate were measured continuously using finger plethysmography. Blood lactate concentration, rating of

perceived exertion (RPE), flow-mediated dilation (index of endothelium-dependent vasodilation), and cardio-ankle vascular index (measure of arterial stiffness) were assessed before and after the walking exercise. **Results:** At baseline, no significant differences existed in any of the variables between the three conditions. Increases in heart rate were greater ( $p<0.05$ ) in the WR than the NE and control conditions. Increases in systolic and diastolic blood pressure were greater ( $p<0.05$ ) in the WR than the NE and control conditions, and increases in systolic blood pressure were greater ( $p<0.05$ ) in the control than the NE condition ( $150\pm16$  /  $85\pm15$  mmHg vs.  $127\pm10$  /  $66\pm12$  mmHg vs.  $130\pm15$  /  $66\pm13$  mmHg, respectively). Double product, an index of myocardial oxygen demand, increased to a greater extent in the WR than in the NE and control conditions, and to a greater extent in the control than the NE condition. Increases in perceived exertion and blood lactate concentration were greater ( $p<0.05$ ) in the WR compared with the NE and control conditions ( $p<0.05$ ), while no differences were seen between the NE and control conditions. There were no changes ( $p>0.05$ ) in arterial stiffness or endothelial function in all three trials. **Conclusion:** Use of wide-rigid BFR cuffs result in a marked increase in blood pressure and myocardial oxygen demand compared with narrow-elastic BFR bands, suggesting that narrow-elastic bands present a safer alternative for at-risk populations to perform BFR exercise.

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## **Review of Literature**

### **Blood Flow Restriction: Background**

Blood flow restriction (BFR) training is an increasingly popular form of exercise, first introduced in Japan more than 20 years ago as Kaatsu, or “additional pressure”. The technique involves placing pressurized bands on the upper portion of the extremities to restrict blood flow during low-load exercise in order to elicit similar adaptations achieved with traditional heavy-load or exhaustive exercise (Takarada et al. 2000). BFR takes advantage of the normal adaptive responses to training by creating a metabolic crisis in the muscle via venous pooling in the limb that results in a mismatch between ATP demand and supply, local hypoxia, acidosis, recruitment of high-threshold motor units, and eventually fatigue (Robergs et al. 2004, Kawada et al. 2005, Spranger et al. 2015). The local fatigue and hypoxia induced in the muscle distal to the cuff stimulates a systemic neurohumoral response to upregulate protein synthesis, muscle hypertrophy, angiogenesis, osteogenesis, and glycogen storage (Takarada et al. 2002, Burgomaster et al. 2003, Yasuda et al. 2005, Larkin et al. 2012, Spranger et al. 2015).

The original form of BFR utilized relatively narrow (3-5 cm) pneumatic elastic belts, but as the maneuver spread outside of Japan, other forms of BFR equipment emerged. One said form was adapted from pneumatic blood pressure cuffs, which are relatively wide (13-18 cm), and typically comprised of inelastic nylon material. While both cuff types can be effective (Abe et al. 2010, Loenneke et al. 2012, Lowery et al. 2014), they may vary in the degree of cardiovascular risk, particularly for clinical populations, who are more prone to exaggerated sympathetic responses during intense

exercise (Baccelli et al. 1999, Bakke et al. 2007, Spranger et al. 2015). Walking in combination with the original narrow-elastic bands improves muscle hypertrophy and strength in trained athletes without overt cardiovascular risk (Takarada et al. 2002, Yasuda et al. 2005). However, walking exercise in combination with pressurized wide-rigid cuffs can elicit significant cardiac stress, vascular dysfunction, and exaggerated blood pressure responses to exercise (Renzi et al. 2010, Sugawara et al. 2015).

Understandably, concern has been raised about the cardiovascular safety risks associated with BFR exercise, and specifically the potential for a sympathetically-mediated increase in blood pressure known as the exercise-induced pressor response or reflex (Renzi et al. 2010, Spranger et al. 2015).

## **Efficacy**

Early studies showing the efficacy of BFR in combination with light-load exercise were first conducted in Japan using the original Kaatsu belts (Takarada et al. 2000, Takarada et al. 2002, Abe et al. 2006). After determining the pressures necessary for sufficient venous blood-flow restriction in five healthy males, researchers implemented a 16-week exercise protocol comparing 24 post-menopausal women across three groups; light-intensity (30-50% of 1 repetition maximum (1RM)) without occlusion (LI), light-intensity with occlusion (LIO), and high-to-medium intensity (50-80%1RM) without occlusion (HI). Using single-arm bicep curls as the training protocol, researchers found that the LIO group achieved greater gains in muscle strength and hypertrophy than the LI group, and equal to the gains achieved in the HI group (Takarada et al. 2000). This landmark study showed that gains in strength and muscle mass using BFR are similar to

traditional resistance training in older women. However, since these older women were untrained, the researchers conducted a follow-up study to investigate the effects of BFR on well-trained young rugby players. Using a similar randomized design, the LIO group exhibited significant increases in knee extension torque and muscle hypertrophy compared with the LI group after 16 sessions of knee extension exercises implemented over 8 weeks (Takarada et al. 2002). The findings of these two studies suggest that performing light-load exercise in concert with BFR results in adaptations normally achieved with high-load training. Another research group found significant increases in thigh muscle cross-sectional area (CSA) and strength in just 3 weeks of twice-daily BFR-walking exercise performed 6 days per week (Abe et al. 2006). Importantly, upon assessment of muscle fiber damage via plasma levels of myoglobin and creatine kinase, no differences emerged between the BFR-walking group and the control-walking group, suggesting that the observed muscular adaptations occurred in the absence of muscle damage. These results highlight the potential use of light-intensity aerobic exercise, which is commonly used to treat atherosclerosis, in combination with BFR to induce physical adaptations without damage to the working muscle.

### **Safety Concerns**

As the purported benefits of the technique spread, Japanese physicians began to use BFR to treat clinical populations, which prompted a group of researchers to conduct a national survey on the incidence of untoward serious complications associated with BFR, including deep-vein thrombosis, rhabdomyolysis, and pulmonary emboli (Nakajima et al. 2006). The survey assessed 105 certified clinics, hospitals, training gyms, and

rehabilitation centers using Kaatsu. Approximately 13,000 users (55% females, 45% males) ranging from the ages of 20-80 years, exhibiting a multitude of diseases (e.g., obesity, cardiac diseases, neuromuscular diseases, diabetes, hypertension), and performing a variety of exercise regimens (resistance, aerobic, combined) reported their experiences. Perhaps surprisingly, the incidence of the proposed side effects of BFR (deep vein thrombosis, rhabdomyolysis, and pulmonary embolism) were rare (0.055%, 0.008%, and 0.008%, respectively), suggesting that this form of BFR as implemented by trained Kaatsu instructors, is a safe and effective means of exercise and treatment (Nakajima et al. 2006). A follow-up survey conducted in 2016 further supported the use of BFR with a wide variety of clinical populations such as orthopedic, cardiovascular, and neuromuscular disease patients (Yasuda et al. 2017), concluding that the use of Kaatsu i.e. narrow-elastic BFR by trained instructors is safe and without overt risk to people of all ages, genders, and fitness levels.

### **Spreading West**

As the use of BFR became more widespread, Western researchers started using the available equipment in their laboratories, such as surgical tourniquets, straps, and blood pressure cuffs to study BFR (Burgomaster et al. 2003, Renzi et al. 2010, Sugawara et al. 2015). These researchers did not use the original Kaatsu belts, in part, due to the very limited availability of the equipment and training. Even in Japan, there is a need for high annual licensing fees (~\$4,000/year), high equipment costs (~\$16,000), and extensive education for certification. Therefore, over the past decade in which the incidence of BFR research increased, the fundamental design and principles used in the

original Kaatsu bands were mixed with wide, pneumatically-controlled, rigid nylon cuffs (Loenneke et al. 2013). This seemingly small detail has led to hundreds of studies that use a variety of BFR equipment, which may elicit different physiological responses.

In fact, researchers concerned with the unintended risks associated with BFR have suggested that instructors take caution, especially when training at-risk populations (e.g., hypertensive, atherosclerosis, obese, diabetic), due to their heightened sympathetically-mediated blood pressure responses to exercise (Irving et al. 2007, Renzi et al. 2010, Spranger et al. 2015). This concern is of great importance considering that BFR is suggested to be a highly efficient and effective form of exercise for clinical patients exhibiting frailty and an inability to tolerate heavy exercise (Takarada et al. 2000, Burgomaster et al. 2003, Abe et al. 2006, Abe et al. 2010, Araújo et al. 2014, Mikesky et al. 2017). In particular, the relatively short duration of exercise (15-30 minutes), and the ability to promote both aerobic and anaerobic fitness via myogenic and angiogenic adaptations make BFR a versatile and practical tool for clinicians (Spranger et al. 2015). BFR training has even been suggested during space flight for astronauts who experience extreme deconditioning due to microgravity, and typically exercise for multiple hours per day in an effort to reduce the rate of atrophy (Hackney 2012). The multitude of applications of BFR make it a useful and promising technique that can be administered to a wide range of the population.

However, the safety concerns associated with BFR may be due to the type of BFR device utilized, and specifically, the transition from elastic Kaatsu belts to inelastic surgical tourniquets, blood pressure cuffs, or straps that inhibit the working muscle from

expanding upon increased blood flow accompanying exercise. Indeed, wide-rigid cuffs appear to increase blood pressure and myocardial oxygen demand by augmenting regional and systemic vascular resistance in addition to the accumulation of metabolites, and subsequent stimulation of chemo- and mechanoreceptors (Renzi et al. 2010, Spranger et al. 2015). Additionally, investigators recorded heightened heart rate and blood pressure responses during wide-rigid BFR training compared to narrow-elastic BFR training (Loenneke et al. 2012). Therefore, the discrepancy between early Kaatsu studies and more recent studies may be indicative of differences in cuff width, pressure, and material used to elicit sufficient blood-flow restriction.

### **Standardization of Protocols and Equipment**

In an effort to ascertain the different effects of various forms of BFR, researchers conducted a series of studies addressing differences in cuff width and material (Loenneke et al. 2012, 2013, 2014, 2015). First, investigators assessed the effects of cuff width on percent arterial occlusion pressure and found that wide (13.5 cm) cuffs occlude arterial inflow at lower pressures than narrow (5 cm) cuffs (Loenneke et al. 2012). Investigators then controlled for cuff width by comparing narrow (5 cm) inelastic nylon cuffs to narrow (5 cm) elastic cuffs, and found no significant difference in arterial occlusion pressure, suggesting that cuff width is more important when determining BFR pressure than cuff material (Loenneke et al. 2013). However, these measurements were conducted at rest, which is not indicative of blood flow elicited during exercise as hemodynamics change dramatically from rest to intermittent, isometric, or continuous exercise (Rowell 2003). Additionally, the skeletal muscle pump plays an essential role during elastic BFR,



in which the muscle is able to force blood past the venous blockade, allowing intermittent venous flow from the muscle. Without the muscle contraction enabling the muscle pump to function, there is little-to-no venous outflow, so pressures necessary for restriction are relatively low at rest compared to exercise.

In a comprehensive review of the differences in BFR equipment and protocols, Loenneke et al. discuss the importance of standardizing BFR training (Loenneke et al. 2013). A key insight was that the determination of cuff pressure sufficient for BFR is primarily dependent on limb circumference, cuff material, and cuff width. It is important to remember that cuff pressures should be high enough to restrict venous outflow, but low enough to maintain arterial flow to the muscle (Loenneke et al. 2013). With this in mind, pressures must be prescribed relative to the individual due to variations in body composition, equipment, and BFR experience. Even with regard to wide-rigid cuffs, there is major variation amongst individuals in the relative pressure needed to elicit arterial occlusion (Alastair et al. 2004). Additionally, brachial systolic blood pressure is not indicative of the pressure necessary to induce the desired BFR stimulus, particularly in the lower limbs, where blood pressure is greatly increased due to a combination of increased hydrostatic pressure and pulse pressure amplification (Tanaka et al. 2010, Loenneke et al. 2013). With this in mind, limb circumference appears to be the primary determinant of cuff pressure when performing BFR, as this is also the case for surgical tourniquets (Crenshaw et al. 1988). However, since it may be advantageous to minimize the amount of arterial occlusion while maintaining adequate venous restriction, and the use of different cuff widths and materials elicit markedly different responses, attempts

should be made to standardize BFR protocols in order to reduce cardiovascular risk to users. For example, arterial occlusion and the mechanical compression of the tissue by the cuff can be painful, which in turn could further augment blood pressure by increasing sympathetic output.

### **Blood Flow Restriction and the Exercise-induced Pressor Response**

Therefore, researchers have called for investigation into the exercise-induced pressor reflex, which may be exaggerated when performing BFR due to the rapid accumulation of metabolites (protons, lactate, other ions) and increased muscle force (Robergs et al. 2004, Spranger et al. 2015). The exercise-induced pressor reflex occurs from the increase in muscle force and the accumulation of metabolites in the muscle that stimulate metaboreceptors and mechanoreceptors. This stimulation results in an increased sympathetic activity, leading to increases in heart rate, contractility, cardiac output, systemic vasoconstriction, and systemic vascular resistance (Spranger et al. 2015). In addition, the venous pooling of blood in the extremities during BFR functionally reduces venous return and stroke volume, which would further increase heart rate in order to maintain the same cardiac output and blood pressure. These potential responses present a perfect storm of stimuli for exaggerated sympathetic activity and could lead to undesirable side effects, particularly in patients prone to heightened sympathetic responses to exercise (e.g., central and peripheral artery disease, hypertension, obesity, etc.). Therefore, it is vital to investigate whether an exaggerated exercise-induced pressor response should be expected when performing BFR before recommending it to at-risk populations.

Loenneke et al. suggests that BFR instructors use relatively low pressures, considering that the use of 40% and 90% arterial occlusion can elicit similar muscular adaptations to BFR training (Loenneke et al. 2015, Counts et al. 2016). Again, these recommendations rely on the use of wide-rigid cuffs designed to occlude arterial inflow. However, since the original purpose of BFR was to restrict venous outflow while minimizing the impediment of arterial flow (Loenneke et al. 2013), it follows that one should not necessarily reduce pressure, but rather reduce the constriction of muscle and vasculature tissues to negate any arterial impediment and allow the skeletal muscle pump to push blood past the venous blockade. This intermittent venous flow is consistently achieved with narrow-elastic cuffs that allow the muscle to expand with increased blood flow upon successive contractions without the need to occlude arterial flow (Takarada et al. 2000). In fact, arterial flow can be reduced by 50% or more when as little as 50 mmHg of pressure is applied to a wide-rigid cuff (Sumide et al. 2009), while arterial occlusion may not occur at pressures exceeding 300 mmHg when using narrow-elastic bands (Loenneke et al. 2013). Thus, it appears that a narrow window of pressures exists for a given individual to utilize the skeletal muscle pump, and perform BFR safely when using wide-rigid cuffs while a fairly large window exists for narrow-elastic BFR.

### **Blood Flow Restriction: Summary**

There are major differences in the literature with regard to cuff materials, pressures, widths, and protocols used to achieve the desired stimulus and adaptations from BFR training. These discrepancies likely stem from a deviation from the original Kaatsu bands, in which the aim was to restrict venous outflow while minimizing arterial

occlusion. In fact, the increase in arterial resistance appears to be unnecessary for the sufficient stimulus for desirable BFR adaptations (Loenneke et al. 2013).

In the ideal BFR session, the goal is to create a proximal venous dam that allows intermittent flow to pass via the skeletal muscle pump. As blood backs up in extremity, it distends, expanding venous and capillary capacitance until distension becomes limited by the outer fascia. With virtually no impact on arterial flow, blood pressure builds until it is greater than the pressure exerted on the veins by the cuff or band, and allows intermittent blood-flow out of the limb. However, most devices used in the literature impact arterial inflow while occluding venous outflow. Thus, investigation into a narrow-elastic cuff that aims to minimize the unwanted side effects of BFR is warranted, especially for use with at-risk populations or the lay athlete who may not understand the underlying physiology. In order to determine the potential cardiovascular risk of two distinct forms of BFR, we will measure the acute cardiovascular responses to a commonly-used protocol, which consists of five 2-minute bouts of low-intensity walking in combination with BFR (Abe et al. 2006, Renzi et al. 2010). Primary outcome measures include heart rate, blood pressure, and other systemic hemodynamics via beat-by-beat finger plethysmography during the exercise in addition to an index of arterial stiffness via cardio-ankle vascular index (CAVI) and endothelium-dependent vasodilation via flow-mediated dilation (FMD) before and after the exercise. Additionally, plasma lactate and rating of perceived exertion will be recorded to assess the relative intensity and effort elicited between the two forms of BFR given the same absolute workload.

## **Endothelial Function**

Vascular endothelial dysfunction, marked by a reduced ability for arteries to vasodilate in response to shear stress or pharmacological stimuli, is an indication of the onset of cardiovascular disease and can be assessed noninvasively via flow-mediated dilation (FMD) (Endemann and Schiffrin 2004). FMD is defined as the percent increase in artery diameter after a period of occlusion.

In response to the reactive hyperemia and subsequent shear stress increase after 5 minutes of occlusion, endothelial cells increase nitric oxide synthase activity, and release the vasodilatory molecule nitric oxide (NO) (Endemann and Schiffrin 2004). NO acts to vasodilate vascular smooth muscle, reducing resistance to flow, inflammation, and platelet aggregation (Endemann and Schiffrin 2004). In a previous study, popliteal FMD was shown to decrease after an acute bout of walking exercise with wide-rigid BFR cuffs, but not after control (Renzi et al. 2010). To assess whether this decrement in FMD is systemic or isolated to the local vasculature distal to the BFR cuff, we will test the brachial artery FMD after an acute bout of walking exercise.

## **Arterial Stiffness**

Arterial stiffness is defined as the physical stiffening of the vascular smooth muscle structure mediated by arteriosclerosis (Tölle et al. 2015), and occurs naturally with aging. Aerobic and combined exercise can improve arterial stiffness in patients exhibiting some degree of cardiovascular disease (Zhang et al. 2018). The severity of arterial stiffness is normally assessed via aortic pulse-wave velocity, with a high-velocity indicating more stiffening due to the pulse-wave amplification and lack of arterial

compliance. The cardio-ankle vascular index (CAVI) is a novel method used to determine the degree of arterial stiffness by assessing pulse-wave velocities between the brachial and tibial arteries (Kubozono et al. 2007). By placing four blood pressure cuffs on the brachial and tibial arteries in the arms and ankles, respectively, one can measure the diastolic and systolic blood pressures at the brachial and tibial arteries (Shirai et al. 2011), and using the foot-to-foot method, can then determine the velocity of the pulse-wave. Due to the combined aerobic and anaerobic stimuli elicited during BFR (Spranger et al. 2015), it may be a useful tool in reducing arterial stiffness over time. In addition, previous non-BFR training studies have shown a slight decrease in arterial stiffness following moderate-intensity aerobic exercise (Kingwell et al. 1997, Kobayashi et al. 2018). Therefore, to evaluate whether this decrease should be expected after a BFR session and to elucidate any differences between wide-rigid and narrow-elastic BFR, we will also assess arterial stiffness via the novel CAVI method.

## **Introduction**

Over the past two decades, blood flow restriction (BFR) training has increased in popularity among athletes, researchers, and physical therapists (Pope et al. 2013). During this form of training, users place pressurized cuffs/bands or non-pressurized straps/wraps on the most proximal portion of the limb in order to restrict venous blood flow while maintaining varying degrees of arterial inflow depending on the cuff (Loenneke et al 2013). The restriction of venous blood flow while performing light-weight exercises leads to venous pooling and a local metabolic crisis that together stimulate systemic adaptations similar to those achieved with heavy exercise (Takarada et al. 2000, Fujita et al. 2008). Since BFR used in combination with low-intensity walking exercise can confer significant improvements in muscle strength and hypertrophy (Takarada et al. 2000, Abe et al. 2005), there is great potential for use with clinical populations for fitness and rehabilitation.

Although BFR training is effective at inducing strength and muscle gains, even during light-intensity walking (Shinohara et al. 1998, Takarada et al. 2000, Abe et al. 2005, Wilk et al. 2018), concern has been raised over the use of BFR with at-risk populations (e.g., hypertensive, obese, atherosclerotic) due to the potential for deep vein thrombosis, rhabdomyolysis, pulmonary emboli (Nakajima et al. 2006, Yashuda et al. 2017), and other serious complications associated with occluding arterial flow and repeatedly contracting muscle. One such complication could be the augmentation of the exercise-induced pressor reflex, which is normally elicited during exercise by the stimulation of local mechano- and metaboreceptors, resulting in a sympathetically-

mediated elevation in blood pressure and heart rate. Since BFR training leads to an accumulation of metabolites and exerts high pressures on the vasculature, it seems likely to elicit an exaggerated blood pressure response (Spranger et al. 2015). Additionally, wide-rigid BFR cuffs can cause painful compression of tissues, increases in systemic vascular resistance, acute vascular dysfunction, and increased myocardial demand even at low absolute intensities (Renzi et al. 2010, Sugawara et al. 2015).

However, many Japanese seniors, athletes, clinicians, and trainers have been using BFR in the form of Kaatsu for over 30 years with an extremely low incidence of serious complications (Nakajima et al. 2006, Yashuda et al. 2017). The more recent findings and resulting concerns may be due to a shift from the original narrow-elastic Kaatsu bands to wide-rigid nylon cuffs adapted from surgical tourniquets and blood pressure cuffs. The wide-rigid cuffs have the potential to inhibit the expansion of muscle upon increased blood flow accompanying exercise and muscle contraction while the narrow-elastic bands do not prevent the expansion. To elucidate the potentially differing effects of these two distinct forms of BFR, we assessed the acute hemodynamic responses of fifteen healthy individuals during low-intensity walking exercise while using wide-rigid cuffs or narrow-elastic bands. We hypothesize that the wide-rigid cuffs will elicit higher blood pressure responses and myocardial oxygen demand compared with the narrow-elastic bands during light-intensity aerobic exercise. Additionally, we hypothesized that systemic endothelial function and arterial stiffness will not be affected by an acute bout of BFR walking exercise. As past investigations using wide-rigid cuffs have led researchers to advise caution when using this technique, this study intends to



determine whether these same blood pressure responses should be expected when using narrow-elastic bands. If discovered that the narrow-elastic bands do not elicit the same heightened blood pressure response to BFR, they may present a safer alternative for at-risk populations predisposed to exhibit exaggerated hemodynamic responses during exercise.

## **Methods**

### **Participants**

A total of 15 young healthy sedentary and recreationally active adults (9 males and 6 females) between the ages of 18 and 35 years (mean age:  $22.8 \pm 2.4$  years) participated in this study. Exclusion criteria for participation assessed via medical history questionnaire included (1) uncontrolled hypertension; (2) smoking within the last 6 months; (3) a history of heart disease, kidney disease, peripheral artery disease, and other known cardiovascular issues; (4) obesity as defined by a body mass index (BMI)  $>30 \text{ kg/m}^2$ ; (5) a history of diabetes or other metabolic dysfunction; (6) major operations within the last 6 months; (7) advised to avoid exercise by a physician; (8) part of a vulnerable population (unable to consent, pregnant women, osteoporotic, etc.): or (9) currently performing BFR training. All participants submitted their written informed consent prior to participation. The Institutional Review Board at The University of Texas at Austin reviewed and approved this study.

### **Procedures**

Participants visited the Cardiovascular Aging Research Laboratory at The University of Texas at Austin on 3 separate occasions for 2.5 hours each visit. During the initial visit, participants read and signed a consent form before filling out a medical history questionnaire. Once completed, we assessed height, body weight, and body fatness using the 7-site skinfold technique with Lange skinfold calipers (Beta Technology, Santa Cruz, CA). Prior to arrival, participants fasted for at least 8 hours, did

not consume alcohol or caffeine for 12 hours, and abstained from strenuous exercise for 24 hours before the session. After 20 minutes of supine rest, researchers recorded baseline measurements of heart rate using a standard three-lead electrocardiogram, blood pressure using an automated sphygmomanometer, arterial stiffness using a pulse-wave velocity index, and brachial endothelial function via flow-mediated dilation in a quiet, temperature-controlled room (23–27°C). In addition to taking plasma lactate samples immediately before and after exercise, we assessed RPE before, mid-way through, and after exercise. During the exercise, we recorded beat-by-beat blood pressure and heart rate continuously via finger plethysmography. Once the participant completed the exercise, we measured heart rate, brachial blood pressure, arterial stiffness, and endothelial function within a 15-minute period. One hour after the completion of the exercise and following 20 additional minutes of supine rest, we again measured heart rate, brachial blood pressure, arterial stiffness, and endothelial function to assess acute hemodynamic responses to the exercise.

### **Experimental Protocol**

After undergoing baseline measurements, each participant performed one of three randomly-assigned walking exercise conditions; walking with pressurized wide-rigid cuffs (WR), walking with pressurized narrow-elastic cuffs (NE), or walking without cuffs (control). Cuffs were placed on both legs and subsequently inflated when performing one of the BFR conditions while no cuffs were used when performing the control. All participants performed the three conditions in a randomized order on three different days, separated by at least 3 days.

### **Arterial Stiffness, Heart Rate, and Blood Pressure at rest**

Researchers measured resting heart rate, brachial blood pressure, and pulse-wave velocity in the supine position using the novel noninvasive cardio-ankle vascular index (CAVI) device equipped with a three-lead electrocardiogram and four blood pressure cuffs (VaSera, Fakuda Denshi, Bunkyo, Tokyo, Japan). The device generates an index score for both the right and left extremities based on the ankle-brachial pulse-wave velocity with a score above 9 indicating possible arteriosclerosis, and a score below 8 indicating no measurable arterial stiffening (Shirai et al. 2011, Saiki et al. 2016). The score is computed by dividing pulse-wave distance by transit-time as measured in the four cuffs.

### **Flow-Mediated Dilation**

Flow-mediated dilation (FMD) is a noninvasive technique used to assess vascular endothelium-dependent vasodilation via the response of the brachial artery endothelium to ischemic stress and the subsequent shear stress during the reactive hyperemia phase. Researchers used a semi-automated diagnostic ultrasound system (UNEXEF-38G, UNEX corporation, Sakae Nakaku, Nagoya, Japan), equipped with a 13-electric linear array transducer operating at 10 MHz. While participants rested in the supine position, we placed a pneumatic cuff on the right forearm with the proximal edge of the cuff just above the participant's antecubital fossa and a second blood pressure cuff was placed on the left arm for standard blood pressure measurements (Tomiyama et al. 2017). We then acquired cross-sectional and longitudinal images of the brachial artery 6-8 cm proximal to the cuff utilizing a semi-automated probe, which self-adjusts to provide clear images of

the intimal layer for baseline artery diameter measurements (Tomiyaama et al. 2017). In order to occlude blood flow, the cuff was subsequently inflated to 50 mmHg above resting systolic blood pressure for a period of five minutes. Upon cuff deflation, blood flow velocity and artery diameter were measured via ultrasound for an additional two minutes. FMD was then calculated via the equation: (maximum diameter – baseline diameter) / baseline diameter x 100 (Tomiyaama et al. 2017).

### **Plasma Lactate Concentration**

Plasma lactate concentration was measured immediately before and within 2 minutes after the walking protocol. Prior to collection of the blood sample, we performed finger-tip asepsis with 70% ethanol solution. Using disposable lancets, we punctured the finger-tip and collected a blood droplet on a disposable lactate test-strip consisting of 1.92 units of lactate oxidase and 0.096mg potassium ferricyanide. All blood samples were analyzed using a portable lactometer (LactatePro, Arkray; Kyoto, Japan).

### **Rating of Perceived Exertion**

Ratings of perceived exertion were assessed before, during, and after the walking protocol. Participants were familiarized with the scale prior to the beginning of the test and asked to score their perceived exertion using the original Borg scale (Borg 1982).

### **Systemic Hemodynamics during Exercise**

In order to record hemodynamics during the walking protocol, beat-to-beat arterial blood pressure waveforms were continuously measured via finger plethysmography (Portapres Model 2, TNO TPD Biomedical Instruments, Netherlands) placed on the middle finger of the left hand of each participant. Participants were

instructed to keep the hand at heart level during the entirety of the exercise session. Systolic, diastolic, and mean arterial blood pressures were estimated from the finger blood pressure waveform with a transfer function (BeatScope 1.0 software; TNO TPD; Biomedical Instrumentation; Amsterdam, The Netherlands). Heart rate was calculated from the finger blood pressure waveform using the validated model-flow method incorporating age, sex, height, and weight (BeatScope 1.0 software, TNO TPD Biomedical Instrumentation, Amsterdam, The Netherlands). Double product, an index of myocardial oxygen demand, was calculated by systolic blood pressure  $\times$  heart rate. The hemodynamic values presented in table 2 and figures 1 and 2 represent the average values during the 2-minute walking bout, excluding the 1-minute rest interval.

### **Blood Flow Restriction Equipment**

We used two commercially-available cuffs as representatives of wide-rigid cuffs and narrow-elastic bands. For the wide-rigid condition, we used wide rapid-inflation pneumatic tourniquets (Hokanson, CC17, Bellevue, WA; 18 cm wide x 108 cm long). For the narrow-elastic condition, we used pneumatically-controlled BFR leg bands (BStrong, Park City, UT; 5 cm wide x 50 cm long).

### **Exercise Protocol**

The walking exercise test consisted of five bouts of 2-minute walking intervals at 0.9 m/s with a 1-minute rest and deflation period between each bout with either wide-rigid cuffs, narrow-elastic bands, or no cuffs placed on the upper thighs (Abe et al. 2006, Renzi et al. 2010, and Sugawara et al. 2015). During the wide-rigid and narrow-elastic BFR conditions, leg blood flow restriction was achieved by applying the cuff near the

inguinal fold on both thighs. Following previous protocols (Abe et al. 2006, Renzi et al. 2010), and in order to familiarize the participant with the wide-rigid cuff, we initially inflated the cuff to 120 mmHg for 30 seconds, released it for 10 seconds, re-inflated to 140 mmHg for 30 seconds, released for 10 seconds, and then re-inflated to the final pressure of 160 mmHg. Standing baseline heart rate and blood pressure was recorded via finger plethysmography for 1-minute before beginning the walking exercise. For the narrow-elastic condition, we gradually inflated the bands to 300 mmHg, which is the recommended and commonly-used pressure for leg BFR according to the company supplying the equipment. These same standard pressures were used for all individuals for comparative purposes. Once the desired pressure was reached, the participants began the walking exercise. After completion of each 2-minute bout, we rapidly deflated both cuffs for 1-minute before the next bout. After the fifth bout, we continued recording blood pressure and heart rate for one additional minute. In the control session, participants performed the same exercise protocol without the application or inflation of either cuff.

### **Statistical Analyses**

In analyzing the results, we used parametric statistics as this data was normally distributed. Since baseline measures for systemic hemodynamics were not different, we used a one-way repeated measures ANOVA to identify significant main effects across the three conditions for systolic blood pressure, diastolic blood pressure, mean arterial pressure, and heart rate averaged during each 2-minute bout. For ratings of perceived exertion, blood lactate, pulse-wave velocity, and flow-mediated dilation, we ran a two-way repeated measures ANOVA to identify group and time effects. After determining

whether significant main effects or interactions ( $p < 0.05$ ) were present, we ran post-hoc multiple comparison t-tests ( $p < 0.05$ ) using a Bonferroni correction to identify the significant differences between conditions. Data are presented as mean  $\pm$  standard deviation (SD).



## Results

Participant characteristics are presented in Table 1. Participants were young, healthy, and exhibited normal body weight and composition. Absolute values for selected hemodynamic variables before and averaged during each 2-minute walking bout are presented in Table 2. Changes in systolic blood pressure, diastolic blood pressure, and mean arterial blood pressure from baseline were averaged during each 2-minute walking bout and are presented in Figure 1. At baseline, no differences existed in any of the variables between the three conditions. Increases in systolic blood pressure, diastolic blood pressure, and mean arterial pressure were greater ( $p=0.001$ ,  $p=0.006$ ,  $p=0.0002$ , respectively) in the wide-rigid condition than the narrow-elastic and control conditions ( $150\pm16$  /  $85\pm15$  mmHg vs.  $127\pm10$  /  $66\pm12$  mmHg vs.  $130\pm15$  /  $66\pm13$  mmHg, respectively) while increases in systolic and mean arterial blood pressure were greater in the control compared with the narrow-elastic condition ( $p=0.0001$ ,  $p=0.003$ , respectively). Changes in double product and heart rate from baseline were averaged during each 2-minute walking bout and are presented in Figure 2. Increases in double product were greater ( $p = 0.0004$ ) in the wide-rigid condition than the narrow-elastic and control conditions ( $13296\pm2016$  vs.  $10526\pm1011$  vs.  $10904\pm1543$ , respectively) and increases were greater in the control compared with the narrow-elastic condition ( $p=0.001$ ). Increases in heart rate were greater ( $p=0.005$ ) in the wide-rigid condition than the narrow-elastic and control conditions ( $89\pm7$  vs.  $83\pm7$  vs.  $84\pm8$ , respectively) whereas no differences in heart rate emerged between the narrow-elastic condition and control ( $p>0.05$ ). Plasma lactate concentrations measured before and immediately after walking

are presented in Figure 3. Increases in plasma lactate concentrations were greater ( $p<0.0001$ ) in the wide-rigid condition than the narrow-elastic and control conditions ( $2.87\pm0.90$  mmol vs.  $1.23\pm0.27$  mmol vs.  $1.07\pm0.22$ , respectively). Ratings of perceived exertion assessed before, mid-way through, and immediately after exercise are presented in Figure 4. Ratings of perceived exertion were greater ( $p<0.0001$ ) in the wide-rigid condition than the narrow-elastic and control conditions immediately post-exercise ( $12.27\pm2.6$  vs.  $7.9\pm1.0$  vs.  $7.3\pm0.5$ , respectively). There was no main effect ( $p>0.05$ ) observed in the cardio-ankle vascular index (CAVI) or flow-mediated dilation (FMD) measures across all three conditions (Figure 5). In all figures with significant differences, a main effect was initially observed, followed by post-hoc multiple comparison analyses.

## Discussion

The present study aimed to elucidate the different hemodynamic responses between two distinct forms of BFR training commonly used by trainers, physical therapists, and researchers. In agreement with previous investigations (Renzi et al. 2010, Sugawara et al. 2015), the use of wide-rigid BFR cuffs elicit markedly increased blood pressure responses and heightened myocardial oxygen demands during light intensity walking compared to narrow-elastic bands and control (Figures 1 and 2). In contrast, the use of narrow-elastic BFR bands did not elicit increased hemodynamic responses compared to control, suggesting that narrow-elastic BFR does not pose additional risk to users than light-intensity walking without BFR. In fact, systolic blood pressure, mean arterial blood pressure, and double product values were greater in the control condition compared with the narrow-elastic condition. This is a novel finding and suggests that narrow-elastic BFR may present a safe option for at-risk populations to perform BFR as a mode of exercise and rehabilitation. Considering that BFR can promote angiogenesis by upregulating local growth factor expression (e.g. VEGF-1, VEGF-2R, GH, etc.) (Larkin et al. 2012), this is of considerable impact to atherosclerotic and hypertensive populations. Additionally, none of the conditions induced acute measurable changes in cardio-ankle vascular indices or flow-mediated dilation, suggesting that these forms of BFR do not promote systemic vascular dysfunction or arterial stiffening, even in the presence of local vascular damage due presumably to reperfusion injury (Renzi et al. 2010).

## **Systemic Hemodynamic Responses**

The mechanisms underlying the differing hemodynamic and metabolic responses to the two forms of BFR exercise remain elusive. However, it is clear that the width and material of the cuff have profound effects on systemic hemodynamics. This is likely due to varying degrees of arterial occlusion and compression of muscle tissue leading to variable increases in blood pressure, systemic vascular resistance, and local mechanoreceptor stimulation (Loenneke et al. 2013, Spranger et al. 2015). In particular, the use of wide-rigid cuffs results in highly compressive forces over a large area of the limb, inhibiting the muscle from expanding with an increase in blood flow accompanying exercise. In contrast, a narrow-elastic design appears to minimize how much working muscle is compressed during repeated muscle contractions, allowing the muscle to swell upon increased blood flow. This is evidenced by the slight drop in diastolic blood pressure during the control and narrow-elastic conditions (Figure 1). The elastic nature of bands enables the distal muscle to force blood past the intermittent venous blockade, minimizing the degree of pain, arterial occlusion, and mechanical compression of tissues while performing BFR. Furthermore, since BFR can be equally effective at inducing hypertrophy and strength gains at 40% and 90% arterial occlusion with the use of wide-rigid cuffs (Counts et al 2015), the percent arterial occlusion may not be of primary concern for an effective BFR session. This is of considerable importance given that an increase in systemic vascular resistance, which is elevated when occluding any percentage of arterial inflow, leads to increases in blood pressure and heart rate due to autonomic reflexes (Spranger et al. 2015). In contrast, during aerobic exercise of varying

intensities, systemic vascular resistance decreases slightly due to a vasodilatory response in the working muscle to exercise (Laughlin 1999). Therefore, the observed increases in systemic vascular resistance during BFR (Renzi et al. 2015, Pinto et al. 2016) is likely a result of the mechanical constriction of muscle and other tissues beneath the cuff that functionally inhibits tissue expansion and reduces the local vasodilatory effects elicited during aerobic exercise. However, when using narrow-elastic bands, this mechanically-mediated rise in systemic vascular resistance appears to be completely absent as the muscle is able to intermittently pump blood past the venous impediment. This is evident by the large increase in diastolic pressure while using the wide-rigid cuffs compared with the narrow-elastic and control conditions. This suggests that the exercise-induced pressor reflex only becomes exaggerated when using wide-rigid cuffs at a commonly-used pressure of 160 mmHg, prompting the need for individualized pressures and use of narrow-elastic bands with at-risk populations.

### **Rating of Perceived Exertion and Plasma Lactate Concentration**

In addition to hemodynamic responses, the wide-rigid cuffs elicited significantly higher ratings of perceived exertion and increases in plasma lactate concentrations. This suggests a greater accumulation of metabolites in the muscle during the wide-rigid condition than the narrow-elastic and control conditions given the same absolute workload. Although speculative, this could be due to a greater degree of arterial impediment leading to more anaerobic metabolism, and more venous blood pooling as the skeletal muscle pump is unable to push metabolite-rich blood past the occluding cuff. This could potentially be useful when performing low loads in a highly controlled

environment versus a gym or physical therapist clinic with healthy individuals. However, it also poses the risk of an augmentation of the exercise-induced pressor reflex, leading to unnecessary increases in blood pressure to achieve the desired BFR stimulus.

In agreement with a past investigations, participants frequently complained of pain from the compression of the cuff when using the wide-rigid cuffs while no one complained of pain when using the narrow-elastic bands (Rossow et al. 2012). This may have confounded the ratings of perceived exertion seen in the wide-rigid condition since pain can augment relative measures of effort during certain types of exercise (Hollander et al. 2003). More importantly, pain stimulates sympathetic activity, which could lead to an even greater augmentation of the exercise-induced pressor reflex (Spranger et al 2015). However, more investigation into the use of narrow-elastic bands during intense exercise, and the subsequent increase in muscle pain is warranted to determine the mechanism responsible for the differences observed.

### **Flow-mediated Dilation and Arterial Stiffness**

In a previous study, walking in combination with wide-rigid cuffs acutely decreased endothelial function as assessed via flow-mediated dilation (FMD) of the popliteal artery (Renzi et al. 2010). However, other findings suggest an improvement in endothelial function over a 4-week training program (Shimizu et al. 2016). To determine whether the acute decrease previously observed was localized to the vasculature or a sign of systemic endothelial dysfunction, we measured brachial artery diameter changes in response to post-occlusive reactive hyperemia. The values remained unchanged across all conditions and time points, suggesting the decrease previously observed was likely a

consequence of local ischemic-reperfusion injury to the vascular endothelium distal to the cuff, and not a drop in systemic endothelial function. The acute decrease in popliteal FMD previously observed may in fact be a stimulus for improved endothelial function, just as microdamage to the muscle promotes protein synthesis, but more longitudinal studies are needed to elucidate the exact mechanisms.

Additionally, the lack of change in pulse-wave velocity across all three groups suggests that this light-intensity exercise in combination with BFR does not acutely affect arterial stiffness. This is in contrast to previous non-BFR findings showing an acute decrease in aortic and peripheral pulse-wave velocity following a 30-45-minute bout of moderate-intensity aerobic exercise (Kingwell et al. 1997, Kobayashi et al. 2017). The reason for the discrepancy is unclear, but may be due to the brief nature of exercise performed in the present study. However, previous longitudinal studies assessing the effects of resistance and aerobic BFR training programs on arterial compliance found that BFR increased local vascular conductance, but did not affect systemic arterial compliance (Kim et al. 2009, Fahs et al. 2012, Clark et al. 2010), so one would not expect a change in systemic arterial stiffness when performing BFR training.

## **Limitations**

There were several limitations to this study. As the purpose of this study was to acutely determine the relative safety among different forms of BFR in young healthy individuals, there was no measure of long-term efficacy between cuffs. Additionally, the responses of young healthy individuals do not necessarily translate to vulnerable populations, so investigation with specific at-risk cohorts is warranted. Furthermore, the

walking exercise did not elicit the same degree of fatigue in the narrow-elastic condition as the wide-rigid condition, indicating that the workload may not have been adequate for the expected adaptations during a narrow-elastic BFR training program. This may partially explain the smaller rise in blood pressure observed in the narrow-elastic condition versus the wide-rigid condition. However, the low exercise intensity implemented was necessary due to the degree of discomfort experienced when using wide-rigid cuffs and to ensure the same absolute workload between conditions. Finally, since this study only assessed acute responses to walking exercise with BFR, we cannot definitely say whether these responses would be the same for long-term aerobic or resistance training. Clearly, there is a need for further research investigating the cardiovascular effects of various forms of BFR and exercise protocols.

### **Future Directions**

There are several opportunities to further elucidate the mechanisms for the observed responses in the present study as well as the use of BFR various populations and protocols. Firstly, as the present study assessed differences between wide-rigid and narrow-elastic cuffs, further research showing the potential differences between narrow-rigid and wide-elastic cuffs are warranted to further elucidate the cause of the increased pressor response. Although Loenneke et al. 2013 have investigated hemodynamic responses to various forms of BFR at rest, the same measures need to be conducted during exercise. In addition, there is a need for more research on BFR as a rehabilitation tool for hypertensive patients. Although several researchers have found positive effects of a BFR training program on attenuating hypertension (Pinto et al. 2015, Cezar et al. 2016,



Mikesky et al. 2017, Shimizu et al. 2016), more investigation is warranted into the precise mechanism as well as the use of a variety of training protocols. Additionally, clear differences regarding the degree of efficacy between different cuffs types remain unclear in the literature, so investigations utilizing a diverse set of equipment across a variety of training programs are warranted to elucidate any differences regarding the degree of blood-flow restriction, practicality, and efficacy. In all likelihood, there is a spectrum of BFR equipment that can elicit the desired stimulus at various pressures and intensities (Wilk et al. 2018), so individually determining the optimal type of equipment and exercise could provide opportunities for a wide range of the population to use BFR.

## **Conclusion**

The main finding in the present study is that the use of wide-rigid BFR cuffs elicit markedly increased blood pressure responses and a heightened myocardial oxygen demand during low-intensity walking compared to narrow-elastic bands or control. It appears that an exaggerated blood pressure response should only be expected when using wide-rigid BFR cuffs that increase systemic vascular resistance by occluding arterial inflow, compressing tissues, and reducing the ability of the skeletal muscle pump to function. Therefore, we conclude that wide-rigid cuffs may only be safe within a narrow window of pressures and should be conducted in a clinical setting where continuous hemodynamics are monitored.

This makes the use of wide-rigid BFR suboptimal with at-risk populations, particularly if there is a safer form of BFR available. In contrast, the narrow-elastic bands do not seem to elicit an augmented exercise-induced pressor response compared to

control. This is likely due to the ability of the muscle pump to function within an elastic material that stretches upon successive muscle contractions, allowing venous blood to flow intermittently past the restricting band. With each subsequent contraction, blood is pumped out of the muscle at a rate insufficient for the muscle to fully recover, leading to a local metabolic crisis, and signaling the systemic neurohumoral cascade and local muscular adaptations. This finding suggests that at-risk populations can perform BFR without fear of overt cardiovascular risk. By nature of its width and material, it is difficult to minimize the risks associated with wide-rigid cuffs when occluding any amount of arterial blood flow, and so, as previously advised by Renzi et al. 2010 and Sugawara et al. 2015, it should be prescribed carefully.

## Tables and Figures

**Table 1.** Selected participants' characteristics

Age (yr)	23 ± 2
Sex	9M/6F
Height (cm)	174 ± 10
Body weight (kg)	70 ± 14
BMI (kg/m <sup>2</sup> )	23 ± 3
Body fat (%)	17 ± 5

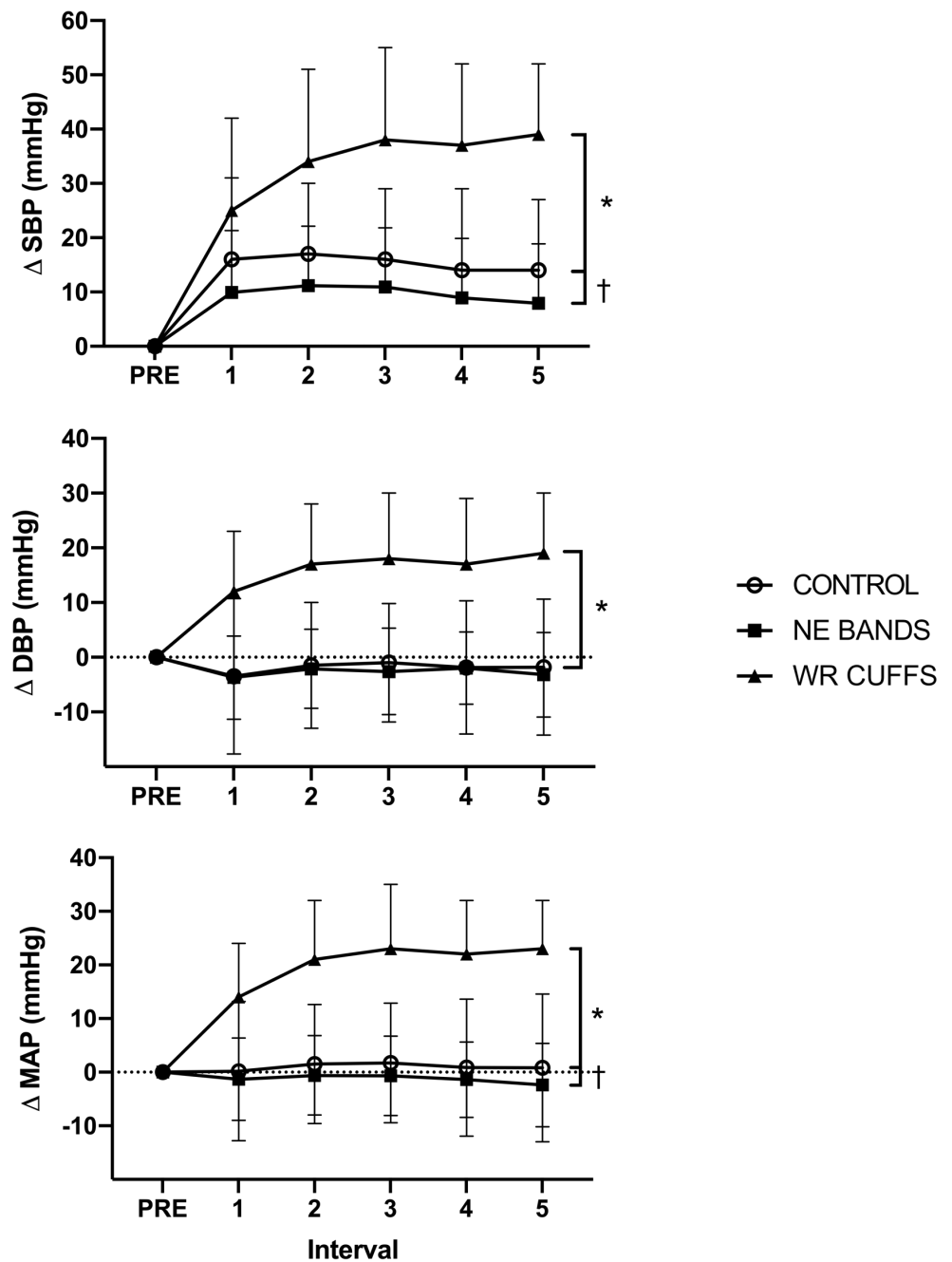
BMI = Body Mass index, Data are means ± SD

**Table 2.** Cardiovascular variables before (Pre) and during (During) an acute bout of walking exercise

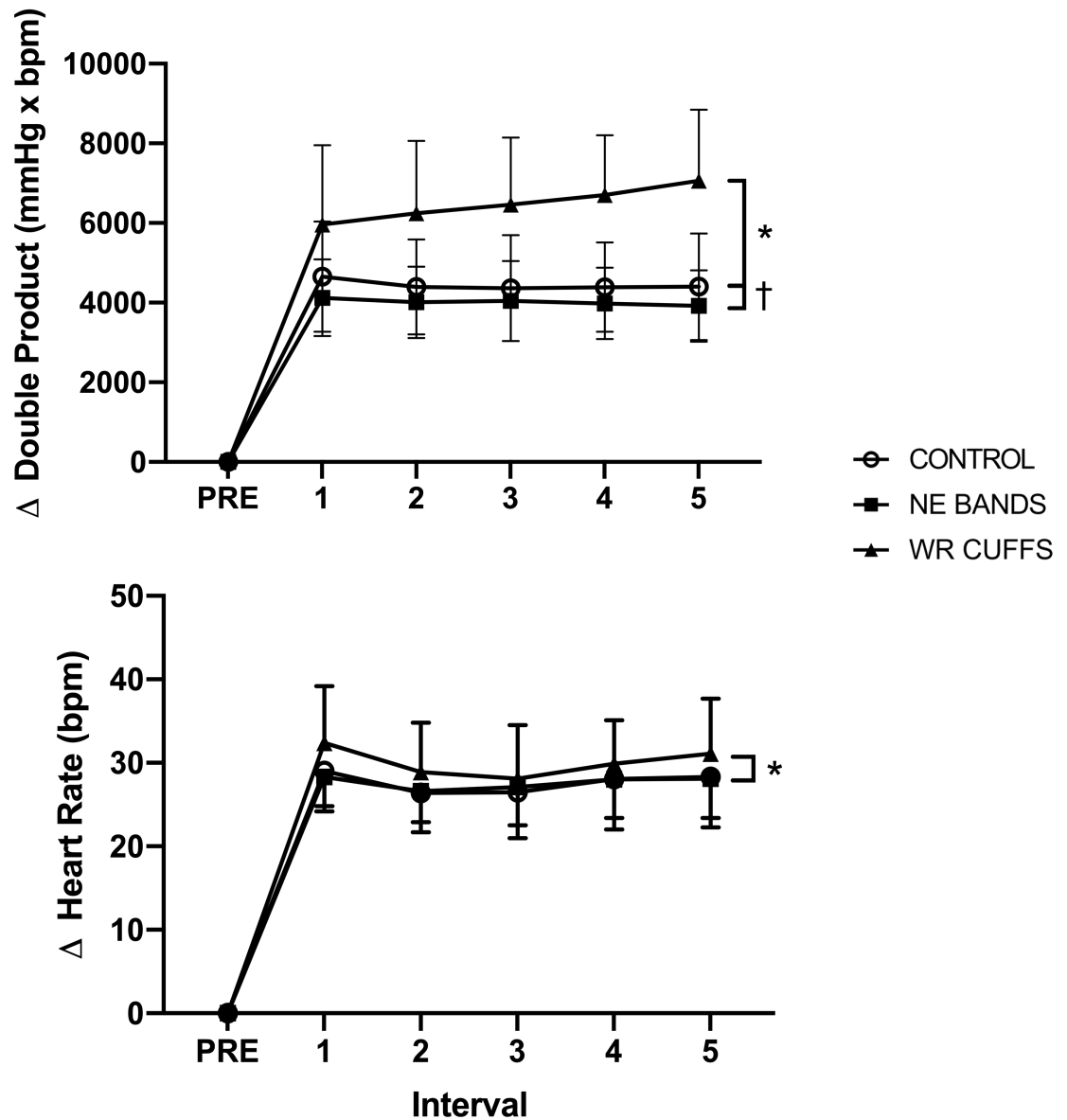
Variable	CON (n=15)		NE (n=15)		WR (n=15)	
	Pre	During	Pre	During	Pre	During
SBP (mmHg)	115 ± 8	130 ± 15	116 ± 9	127 ± 10	116 ± 11	150 ± 16*†
DBP(mmHg)	69 ± 8	66 ± 13	67 ± 7	66 ± 12	66 ± 7	85 ± 15*†
MAP (mmHg)	84 ± 7	85 ± 13	84 ± 7	86 ± 9	82 ± 7	108 ± 17*†
Double Product (mmHg x bpm)	6427 ± 1130	10904 ± 1543*	6488 ± 934	10526 ± 1011*	6984 ± 1472	13296 ± 2017*†
Heart Rate (bpm)	56 ± 9	84 ± 8*	56 ± 6	83 ± 7*	60 ± 9	88 ± 7*†

CON = control condition, NE = narrow-elastic condition, WR = wide-rigid condition, SBP = Systolic Blood Pressure, DBP = Diastolic Blood Pressure, MAP = Mean Arterial Pressure, mmHg = millimeters of Mercury, bpm = beats per minute.

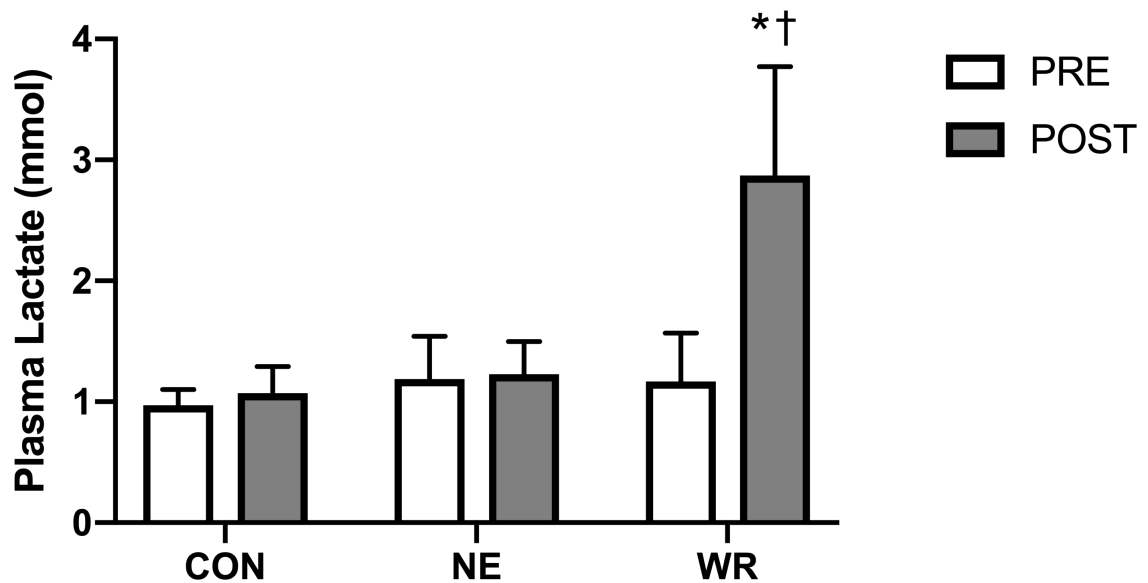
\*P<0.05 from Pre, † P<0.05 from control; Data are means ± SD.



**Figure 1.** Systolic, diastolic, and mean arterial blood pressure before (Pre) and during each 2-minute interval of the walking exercise. Data presented as means  $\pm$  SD. Main effect ( $p=0.001$ ,  $p=0.006$ ,  $p=0.0002$ , respectively), \* $P<0.05$  from wide-rigid, †  $P<0.05$  from control. Data presented as mean  $\pm$  SE.

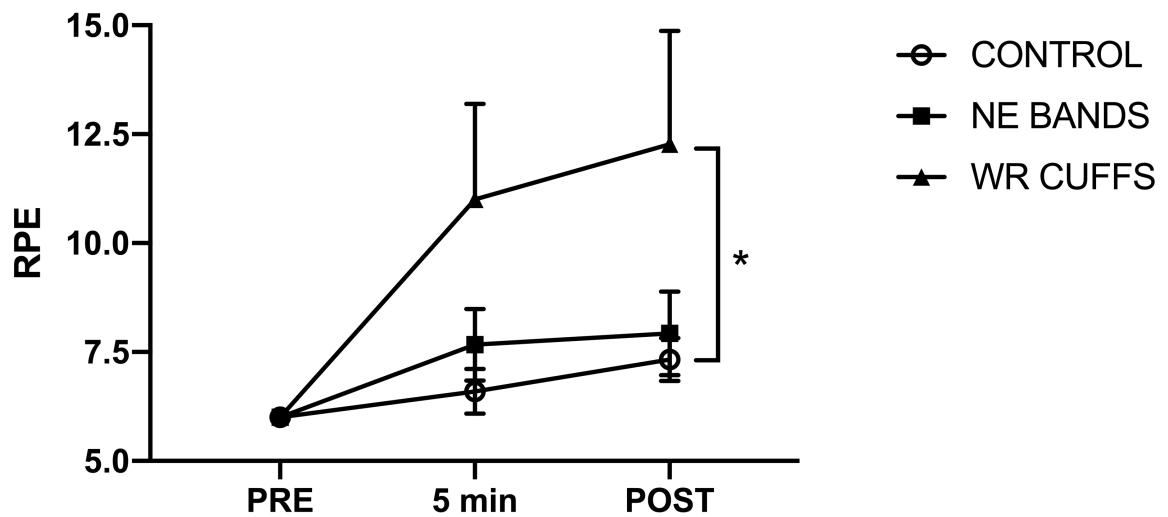


**Figure 2.** Double product and heart rate before (Pre) and during each 2-minute interval of the walking exercise. Main effect ( $p = 0.0004$ ,  $p=0.005$ , respectively), \* $P<0.05$  from WR cuffs, †  $P<0.05$  from control. Data presented as means  $\pm$  SD.

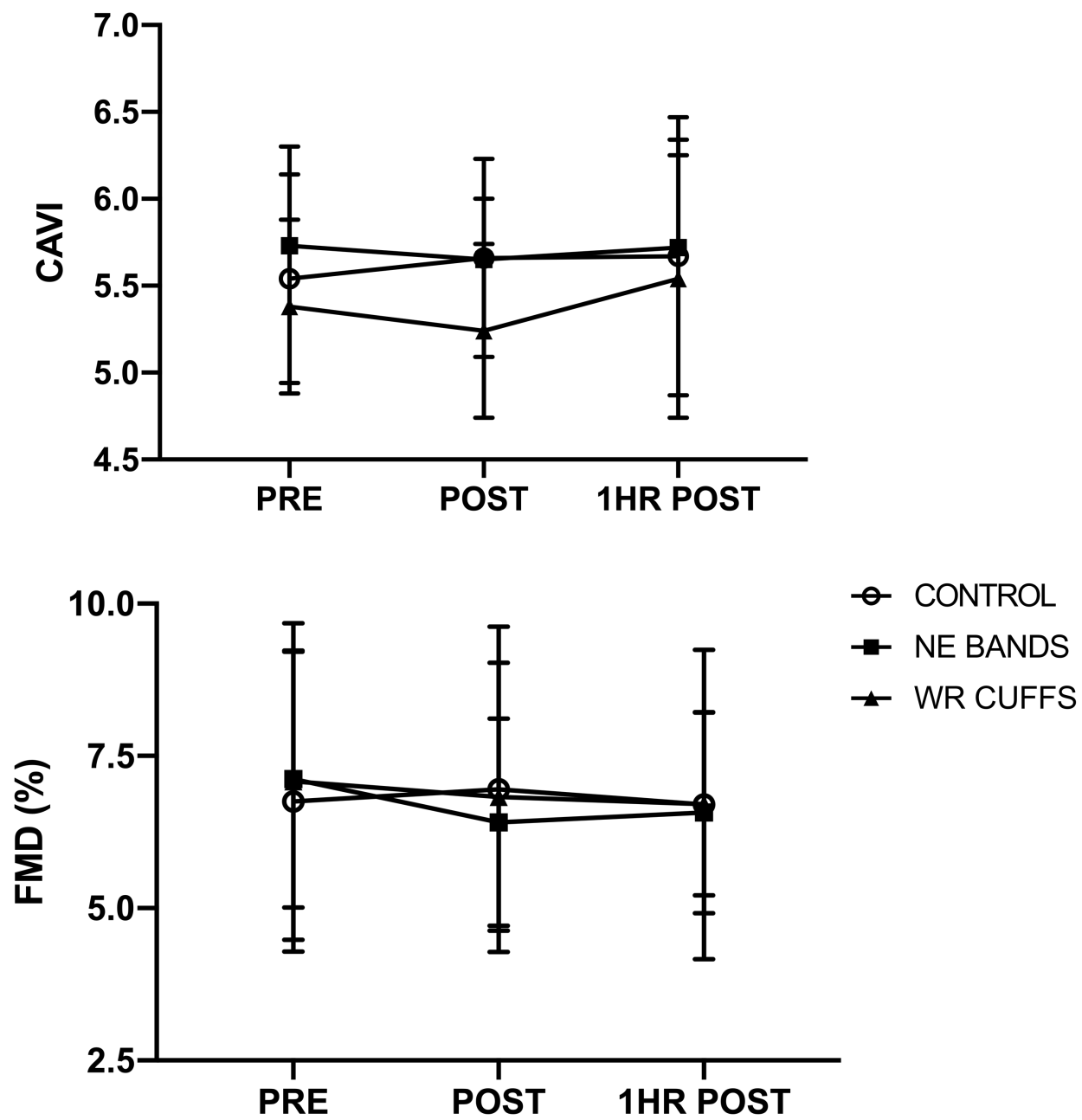


**Figure 3.** Plasma lactate before (Pre) and immediately after (Post) the walking exercise.

\* $P < 0.05$  from Pre, †  $P < 0.05$  from control. Data presented as means  $\pm$  SD.



**Figure 4.** Ratings of perceived exertion (RPE) before (Pre), 5 minutes into the exercise, and immediately after (Post) the walking exercise. \* $P < 0.05$  from Pre, †  $P < 0.05$  from control. Data presented as means  $\pm$  SD.



**Figure 5.** Cardio-ankle vascular index (CAVI) and Flow-mediated dilation (FMD) assessed before (Pre), immediately after (Post), and one-hour after (1HR Post) walking exercise. Data presented as means  $\pm$  SD.



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